Ring-Ring Luminosity Upgrades

MAC 10/21/15

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- Acknowledgment
- Luminosity - number of bunch, scaling
- Round vs. flat beams
- Levels of upgrade
- Divergences and crossing angle
- Beam-beam parameters and decrements
- Parameters
- IBS and cooling
- Duty cycle
- SLAC surplus
- Conclusion

Acknowledgment

The Luminosity upgraded discussed here are based on the "many small bunch" ideas discussed by Durbenev and Zhang, but the constrains used, and resulting parameters are different. In particular, this study considered unequal electron emittances (flat beams) rather than equal emittances (round beams).

Luminosity

$$\mathcal{L} \;=\; \mathrm{f}\, \frac{\mathrm{N_p\ N_e}}{4\pi\sigma_{\mathrm{x}}\sigma_{\mathrm{y}}} \tag{1}$$

The beam dimensions at the IP σ_x σ_y must be the same for both protons and electrons and depend on their emittances and β^*s

$$\sigma_{p,e,x,y} \;=\; \sqrt{\epsilon_{p,e,x,y}\beta^*_{p,e,x,y}} \tag{2}$$

The emittances and particles/bunch $N_{e,p}$ are constrained by beam-beam parameters

$$\xi_{p,e} = \frac{r_{p,e}}{2\pi}\,\frac{N_{e,p}}{\epsilon_{p,e}\ \gamma_{p,e}}\,\frac{1}{(1\ +\sigma_{y,x}/\sigma_{x,y})} \tag{3}$$

and

$$P_e \;\propto\; f\ \gamma_e\ N_e \qquad\qquad P_p \;\propto\; f\ \gamma_p\ N_p \tag{4}$$

Luminosity dependence on β^*s

Combining equations 1 and 2, 3, and 4, we get

$$\mathcal{L} \propto \left(\frac{\mathrm{P_e\ P_p}}{(1+\mathrm{K})(1+1/\mathrm{K})} \right)^{1/2} \left(\frac{\xi_{\mathrm{x,p}} \ \ \xi_{\mathrm{y,p}} \ \ \xi_{\mathrm{x,e}} \ \ \xi_{\mathrm{y,e}}}{\beta^*_{\mathrm{x,p}}\ \beta^*_{\mathrm{y,p}}\ \beta^*_{\mathrm{x,e}}\ \beta^*_{\mathrm{y,e}}} \right)^{1/4} \tag{5}$$

where $K = \sigma_y/\sigma_x$, which, with the geometric definition of the averages, can be written as

$$\mathcal{L} \propto \frac{<\mathrm{P}>}{\sqrt{(1+\mathrm{K})(1+1/\mathrm{K})}} \ \frac{<\xi>}{<\beta^*>} \tag{6}$$

If the beam powers are limited and all beam-beam parameters ξs are bounded, and K is fixed, then luminosity can only be raised by reducing the β^*s

Luminosity dependence on emittances $<\epsilon>$

Again

$$\mathcal{L} \propto \frac{<\mathrm{P}>}{\sqrt{(1+\mathrm{K})(1+1/\mathrm{K})}} \frac{<\xi>}{<\beta^*>}$$

But to limit the size of focus elements, we must constrain the beam divergence angles $\sigma'_{p,e,x,y}$ from the IP

$$\sigma'_{p,e,x,y} = \sqrt{\frac{\epsilon_{p,e,x,y}}{\beta^*_{p,e,x,y}}} \tag{7}$$

the emittances ϵ must be lowered in proportion to the β^*s:

$$\mathcal{L} \propto \frac{<\mathrm{P}>}{\sqrt{(1+\mathrm{K})(1+1/\mathrm{K})}} \frac{<\xi>}{<\epsilon>}$$

Luminosity dependence on number of bunches

As the emittances are lowered, to constrain the beam-beam parameters ξ

$$< \xi > \;\; \propto \; \frac{< N >}{< \epsilon >}$$

the numbers of particles in the bunches $N_{e,p}$ must also be lowered, and noting that the beam powers $< P >$ are $\propto N_b \;\; < \gamma \; N >$

$$\mathcal{L} \; \propto \; \frac{\mathrm{N_b} < \gamma > \quad < \mathrm{N} >}{\sqrt{(1+\mathrm{K})(1+1/\mathrm{K})}} \;\; \frac{< \xi >}{< \mathrm{N} >}$$

Cancelling the $< N >$s, and for fixed K:

$$\mathcal{L} \propto \frac{< \gamma \; \xi >}{< \beta^* >} \propto \frac{< \gamma \; \xi >}{< \epsilon >} \propto \frac{< \gamma \; \xi >}{< \mathrm{N} >} \propto \; \mathrm{N_b} \;\; < \gamma \; \xi > \tag{8}$$

RF scaling

- It is clear that, for higher luminosities, cooling will be required in both transverse and longitudinal phase space.
- To maximize the longitudinal emittance, and minimize cooling, we should use rf to keep the momentum spread as close as possible to its accepted maximum ($\approx 5\ 10^{-4}$)
- To minimize the needed rf Voltage, the frequency should be as high as possible, consistent with the bunch length:

$$f \propto \frac{1}{\sigma_z} \propto \frac{1}{\beta} \propto \mathcal{L} \text{ etc.} \tag{9}$$

- Now with a fixed momentum spread:

$$\epsilon_p = p \frac{dp}{p} \sigma_z \propto \beta \propto \frac{1}{\mathcal{L}} etc. \tag{10}$$

So RF frequency and longitudinal emittances also scale

Round vs. Flat Beams

The expression $(1+K)(1+1/K)$ in equation 5 is minimized when $K = 1$, i.e. round beams are favored

Also, for fixed beam powers, the maximum luminosity is obtained when all beam-beam parameters, are at their limits, both in x and y. This also implies an advantage for round beams. But the real situation is more complicated. There are many constraints besides those for the ξs, and the advantages of round beams appear not so large.

In addition, maintaining polarization, while demonstrated for flat beams at HERA, is not certain for round.

So, as in the baseline, the parameters for the upgrades will be for the flat case.

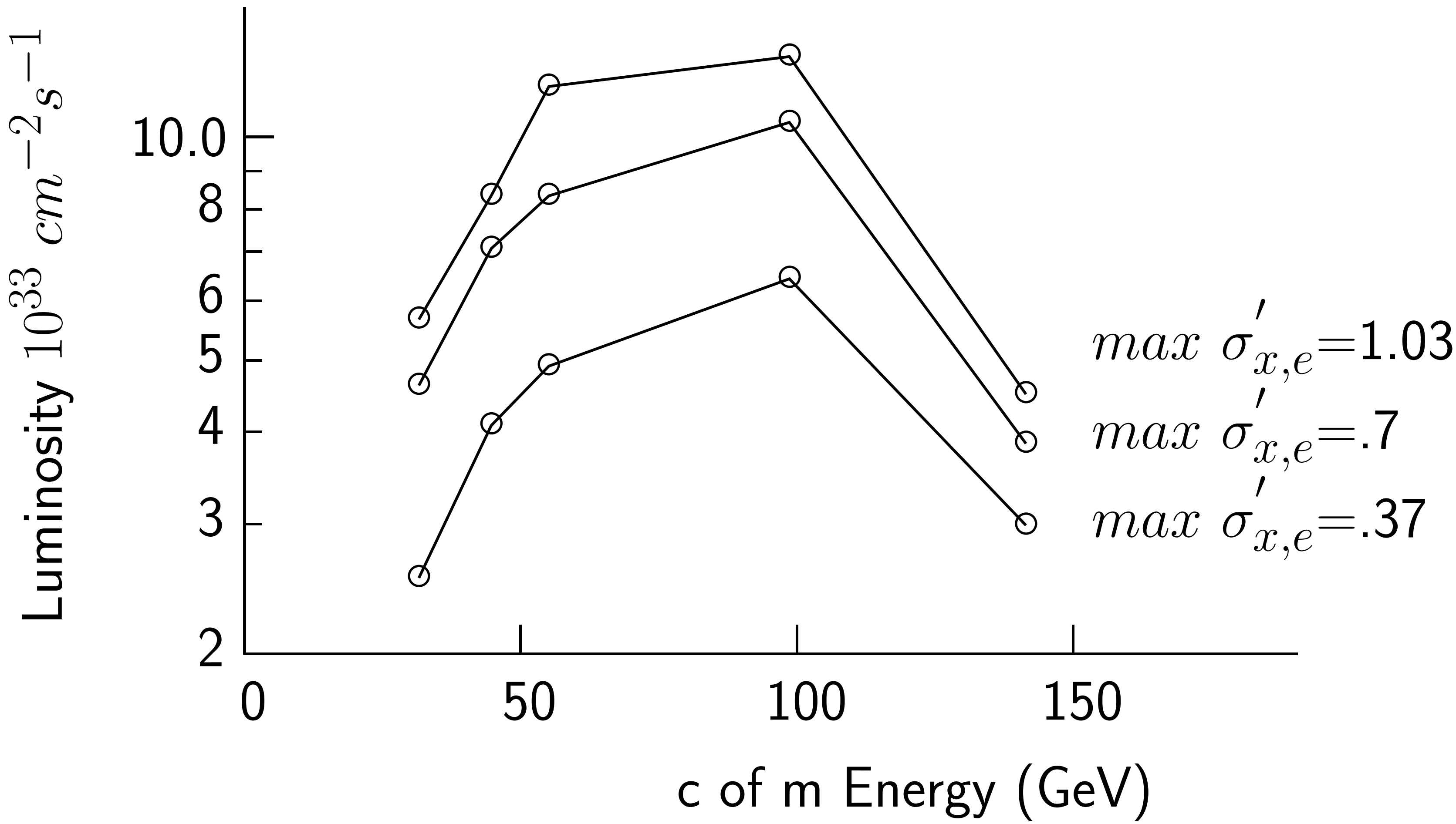
Two Levels of Upgrade

Parameters have been sought for two sets of constraints

Level		Base	upgrade 1	Upgrade 2
Crossing Angle	mrad	15	22	22
Maximum number of bunches		360	2000	6000
Maximum electron divergence $\sigma'_{x,e}$	mrad	0.37	0.7	0.7
Minimum e horizontal emittance	μm	53	23	10
Norm. trans. p transverse emittances	μm	2.5	0.7	0.34
Maximum proton divergence $\sigma'_{x,p}$	mrad	0.42	0.47	0.40
Minimum proton β^*	cm	27	8	4
Minimum proton bunch length	cm	20	8	3.5

- The two levels were aimed at 1) electron cooling, and 2) CeC
- But it is not clear that level 2 cannot be achieved with magnetic electron cooling

Performance vs. electron divergence $\sigma'_{x,e}$



- This example shows luminosities with 3 different max divergences.
- Significant gain between 0.37 and 0.7. Lesser gain for 1.03 mrad.
- On this basis, the maximum divergence of 0.7 mrad was selected

Crossing Angles with increased $\sigma'_{x,e}$

- The upgrade electron maximum divergences σ'_x are $\approx 2 \times$ those in the baseline: 0.7 mrad vs. 0.37 mrad
- Assuming the focus triplet's physical acceptance $= 15 \times \sigma'_x$, then the crossing angle must be increased by $0.33 \times 15 \approx 5$ mrad: 20 mrad vs. 15 mrad
- Another 2 mrad was added to allow earlier proton dipole elements to reduce the distance to a proton triplet.
- At the same frequency, this would require higher crab cavity rf voltages,
- But the upgrade's shorter proton bunch lengths allow higher crab cavity frequencies, minimizing or eliminating the increased voltages

Allowed electron beam-beam parameters

Electron storage ring data has found the requirement:

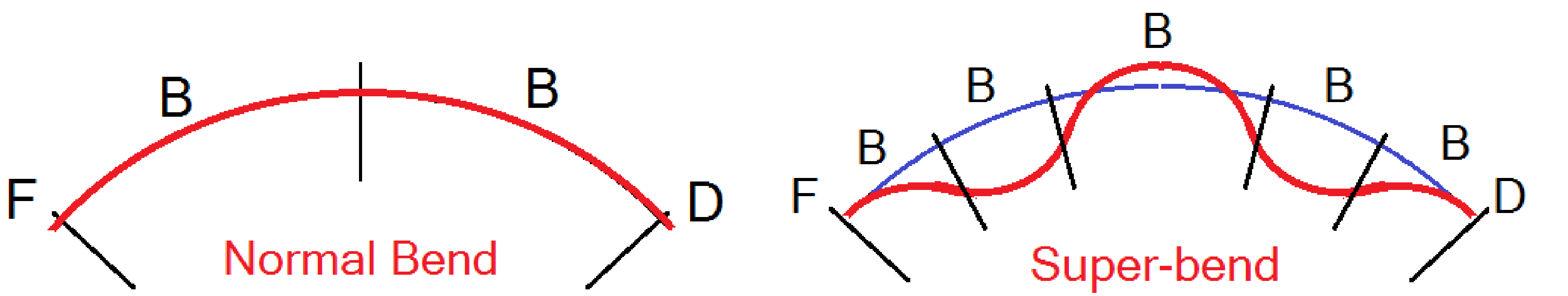
$$\xi_x \le 1.37 \left(\frac{\Delta E_e}{2\ E_e}\right)^{1/3}$$

With normal arc lattices, the synchroton energy loss:

$$\Delta E_e \propto \gamma^4$$

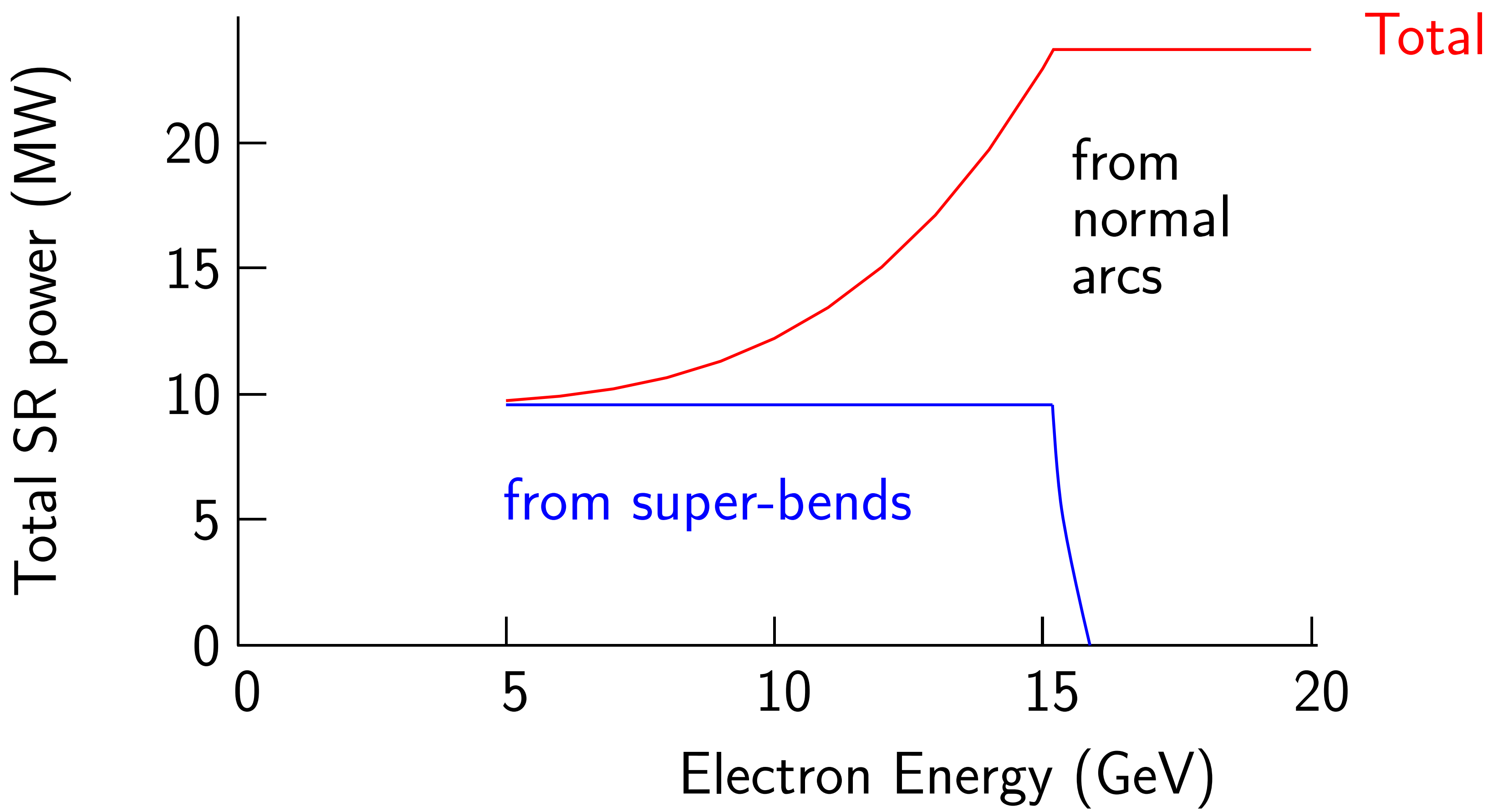
so the ξ bound is very low at lower energies

Super-bends, with higher fields, allow ΔE_e bounded only by a SR limit of 10 kW/m, independent of γ_e

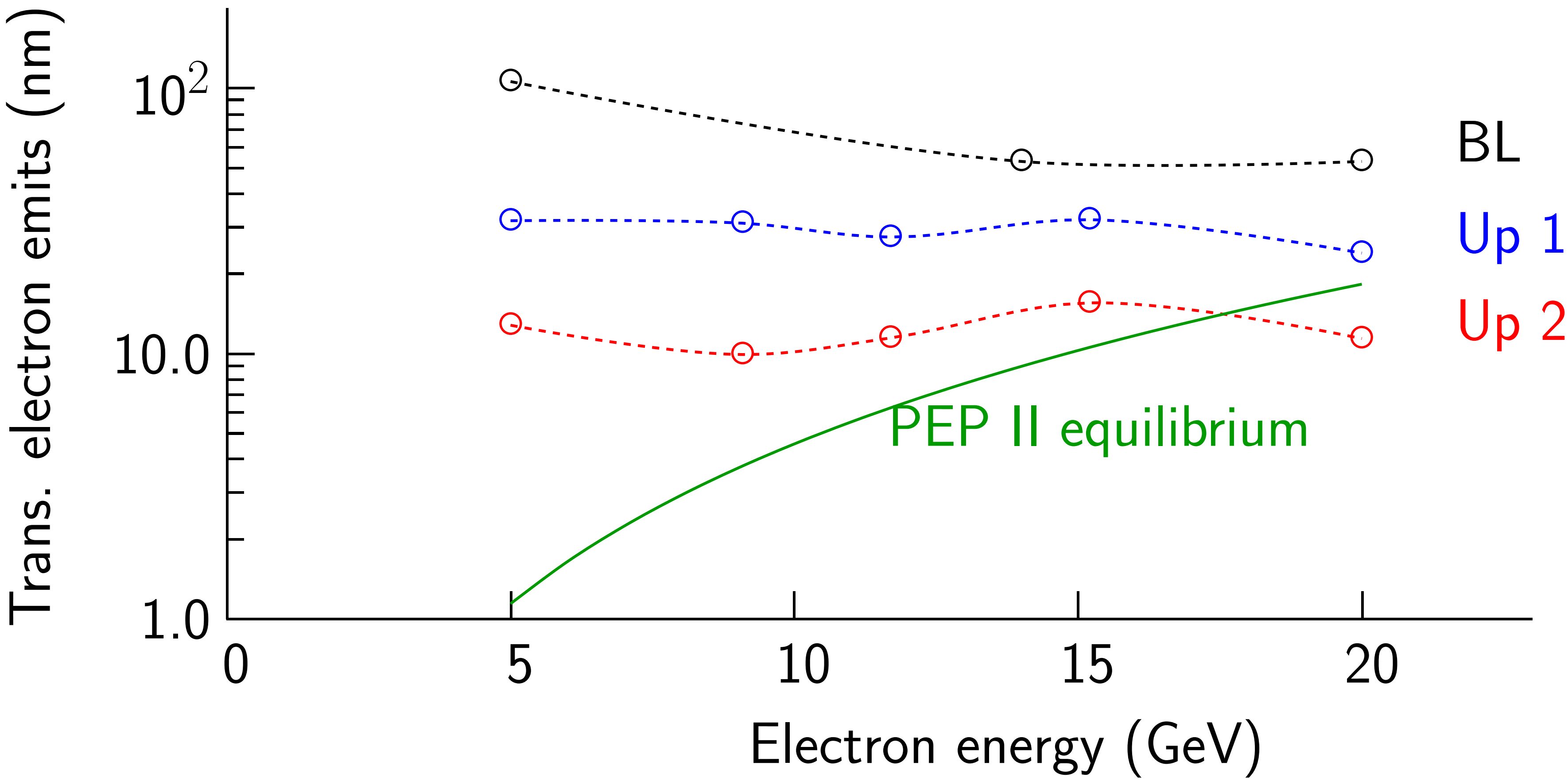


SR power with super-bends

- To avoid 24 MW power at all energies
- Only $\approx$ 40% of cells are equipped with super-bends

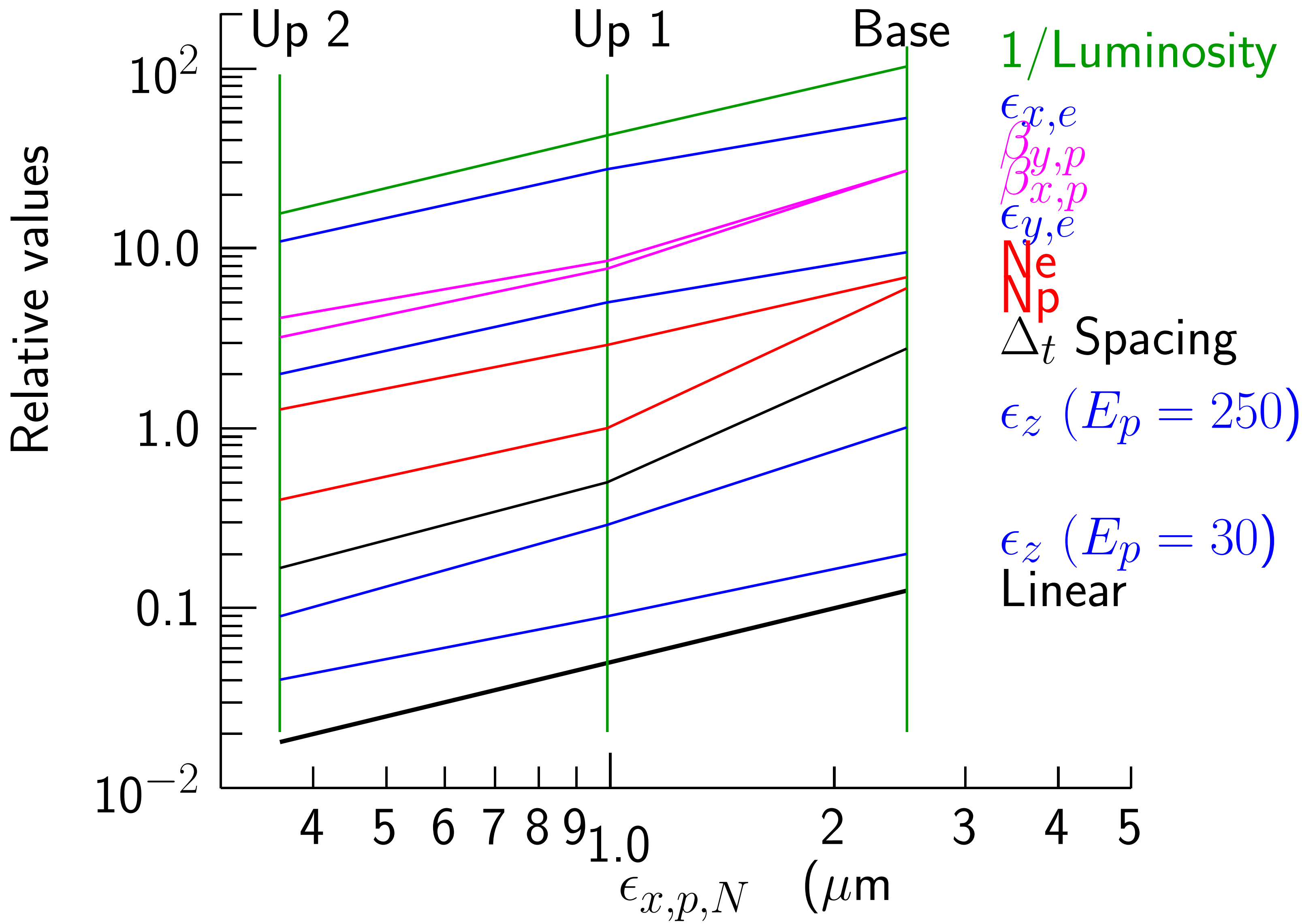


Needed electron emittances



Compromise may be needed for 20 GeV Up 2

Max luminosity parameters vs. upgrade level



For this and lower energies, equation 8 is well demonstrated

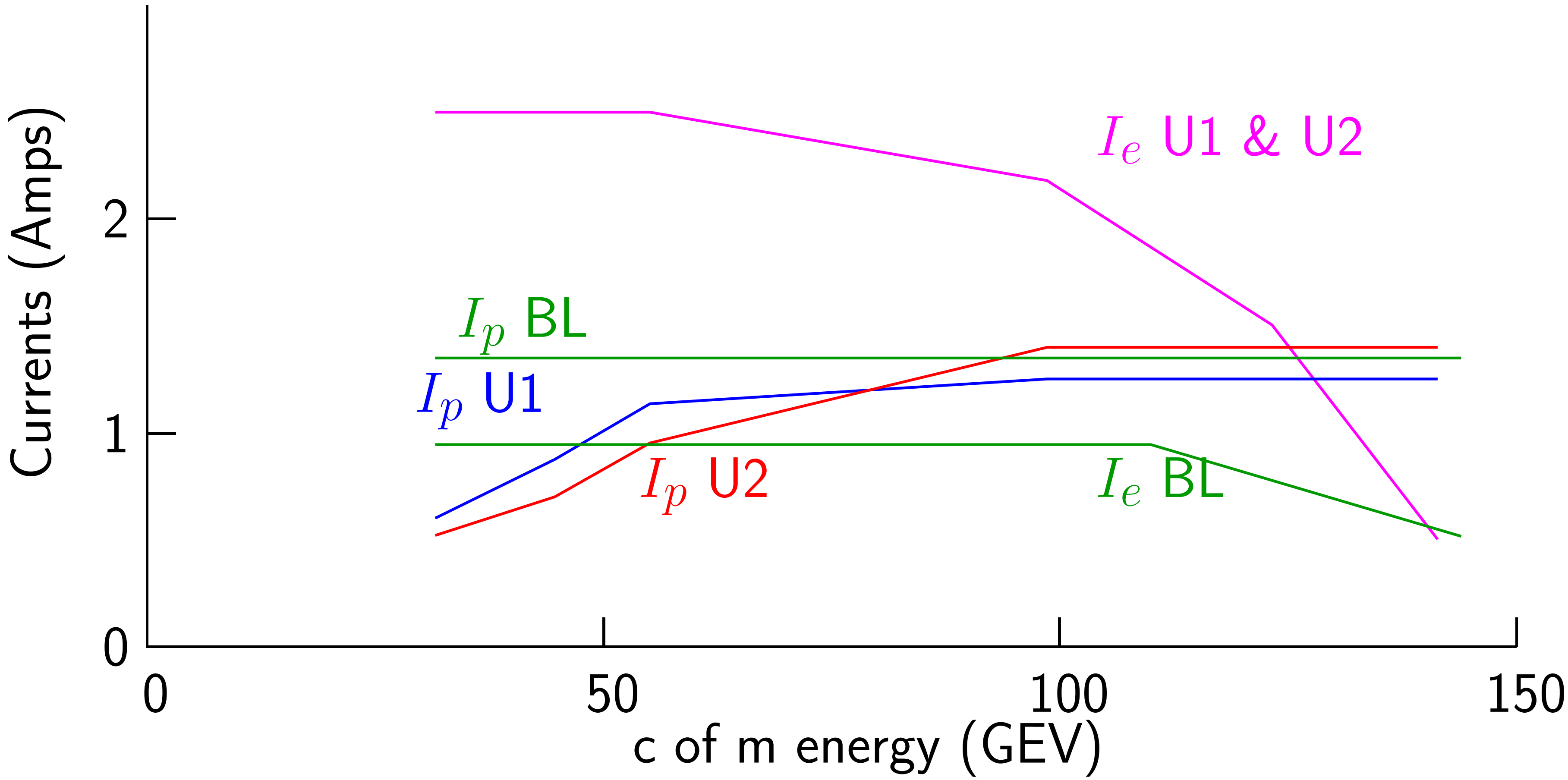
Parameters vs. c of m energies

At each c of m energy a search for maximum luminosity varied:

1. Relative electron and proton energies
2. Electron emittances with $\epsilon_y = \epsilon_x \times 0.18$
3. β_x, and β_y allowing $K = \sigma_y/\sigma_x$ to vary
4. Number of bunches N_b
5. N_e to lower synchrotoron radiation

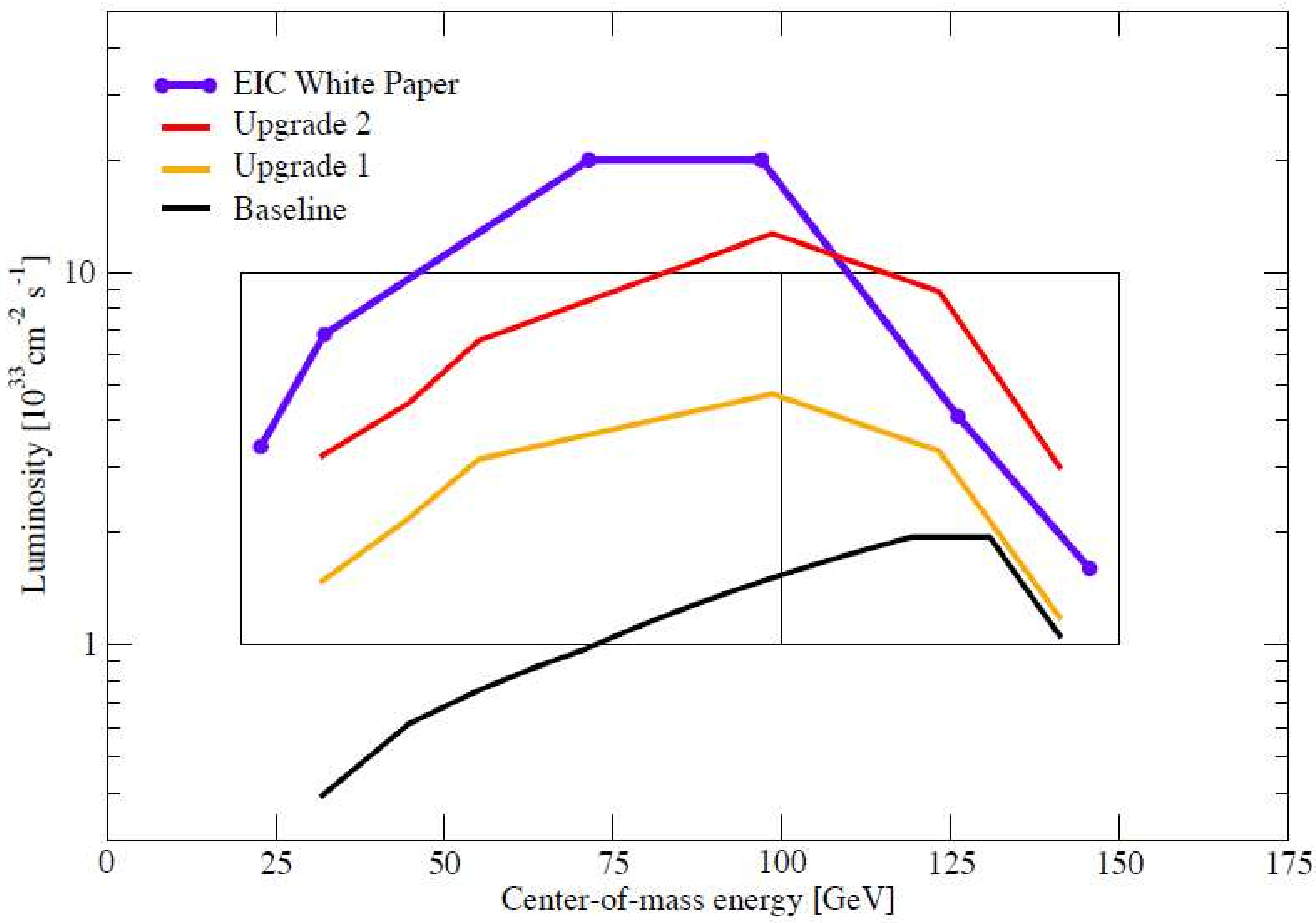
- Detailed parameters given in Appendix I

Average beam currents



- Proton currents similar to Baseline
- Electron current higher based on PEP II (3 A)
- Electron current reduced at high E from SR $\leq$ 10 kW/m

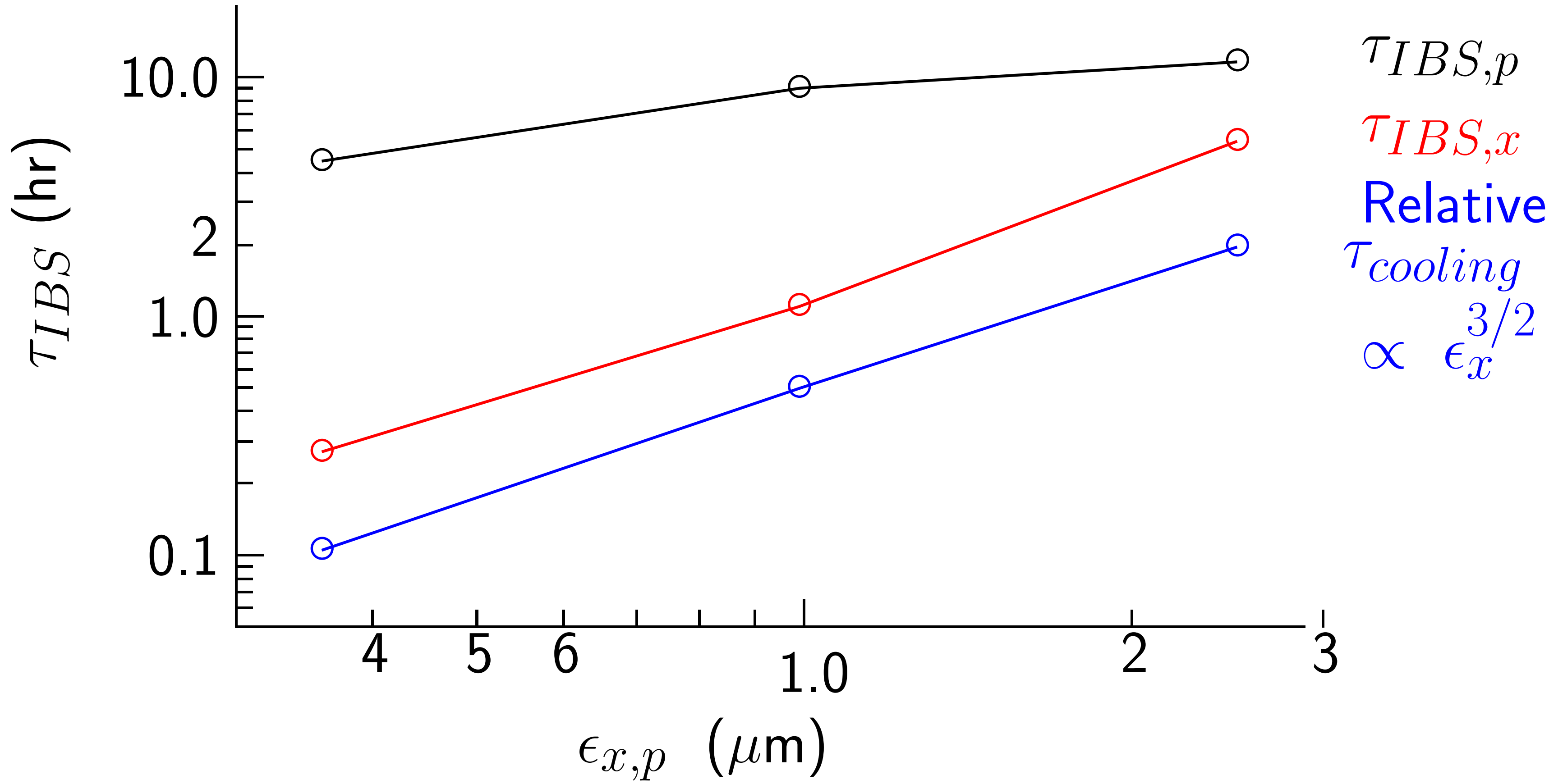
Luminosities



- Gains $\approx$ 10 for lower energies
- Only $\approx$ 3 at max E where synchrotron radiation hurting

IBS growth & Magnetic electron Cooling

For 250 GeV protons and other parameters given in Appendix II



- Rates helped by falling charges per bunch $30 \rightarrow 5 \rightarrow 2$ (10^{10})
- If cooling rate ok at baseline, it will be ok for upgrades

Required cooling

1. Initial proton cooling at low energies

	Base	Upgrade 1	Upgrade 2	
N_p	30	4.6	1.9	10^{10}
$\epsilon_{N,x}$	2.5	1.0	0.34	(μm)
ϵ_p	0.1	0.03,	0.004	(eVs)

2. Continuous cooling at operating energies to stop emittance growth
   - Electron Current $\propto N_b\ \sigma_z\ \epsilon^{3/2}$
   - $N_b\ \sigma_z$ holds constant with scaling
     though not yet in parameters used
   - Dependence on ϵ balances shorter growth times
   - But we do not yet have a design
3. Magnetic electron cooling to $\epsilon_{N,p}\ =\ 0.5\ \mu$m $\rightarrow\ \approx$ Level=1.5
4. Coherent electron Cooling to $\epsilon_{N,p}\ =\ 0.2\ \mu$m $\rightarrow\ >$ Level 2

Detector Duty cycle

- The upgraded scenarios use the same average proton currents, and $\approx 2\times$ the electron currents as in the baseline
- Thus the total beam gas background will be similar
- But it will be distributed over many more bunches: giving less background per bunch crossing

- In the upgraded scenarios, the luminosity rises with the number of bunches, so:
- The interactions per bunch crossing remain similar; So the signal to background ratio will be better

- But some DAQ changes may be needed for the more continuous data flow

Surplus SLAC equipment

1. PEP II equipment maintained since 2008 in situ and well preserved, includes
   - Dipoles, quadrupoles, steering magnets, vacuum chambers, bellows etc. ($\approx$ 60% of need)
   - $\approx$ 20 MV of 476 MHz Cavities, waveguides, klystrons, and power supplies ($\approx$ 50 % of need)
2. 800 m of 2856 MHz linac (15-21 GeV) now running, to be replaced by next year by a super-conducting linac for NCLS II, including:
   - Girders, alignment system, Linac, quads
   - Klystrons, vacuum, controls
   - If used in racetrack or ring RLA (100 % of need)

SLAC equipment for ring-ring eRHIC ?

- PEP II magnets and vacuum system could provide 60% of the eRHIC arcs (40% would need super-bends)
- PEP II rf system well suited to many bunch upgrade designs
  but frequency too high for baseline
- SLAC linac well suited to electron injector for many bunch upgrade designs
  but not suited to large bunch charges in baseline
- Their use would substantially lower the cost of a many bunch upgrade eRHIC design
- But decision needed within two months, and $\approx$ 2 M$ needed, if linac is to be preserved

Conclusion

- There appears, for fixed e and p currents and other constraints, a fundamental correlation between numbers of bunches and maximum luminosities in ring-ring e-p colliders
- Using this correlation is probably the only way to reach eRHIC physics goals with ring-ring
- Lower e and p emittances are required
- The electron ring lattice needs relatively high tunes to lower the e emittance (PEP II lattice probably ok)
- Electron cooling of the protons will be needed a) at low energies to lower the p emittances, and b) at full energy to control Intra-Beam Scattering IBS
- Cooling study needed to judge the practicality and limits of this approach, and to determine if CeC is needed for upgrade 2

Appendix I: Parameters

	E	N	Nb	ϵ_{xN}	ϵ_{yN}	β_x	β_y	σ_x	σ_y	σ'_x	σ'_y	max	ξ_x	ξ_y	ξ_{max}	ΔQ	σ_s	I	SR/m	SR	HG	lum
	GeV	10^{10}		μm	μm	cm	cm	μm	μm	mrad	mrad	mrad					cm	A	kW/m	MW	%	10^{33}
30UP 1	31.6																					
p	50	2.7	1767	0.99	0.99	11.6	8.4	46.5	39.5	0.40	0.47	0.40	.015	.013	.015	.022	8.0	0.60			80	1.47
e	5.0	11.3	1767	31.7*	5.7*	6.8	27.4	47	40	0.68	0.14	0.70	.021	.099	.099	.000	1.2	2.50	4.0	9.6		
P44UP 1	44.7																					
p	55	4.0	1767	0.99	0.99	12.8	9.2	46.5	39.5	0.36	0.43	0.36	.015	.013	.015	.027	8.0	0.88			81	2.18
e	9.1	11.3	1767	31.0*	5.6*	7.0	28.0	47	40	0.67	0.14	0.70	.017	.081	.081	.000	1.2	2.50	4.0	9.6		
55UP 1	55.1																					
p	75	4.7	1923	0.99	0.99	17.4	8.5	46.5	32.6	0.27	0.38	0.27	.015	.010	.015	.017	8.0	1.14			81	3.15
e	10.1	10.4	1923	30.8*	5.5*	7.0	19.1	47	33	0.66	0.17	0.70	.020	.079	.079	.000	1.2	2.50	4.0	9.6		
100UP 1	98.6																					
p	208	5.0	2000	0.99	0.99	48.4	8.5	46.5	19.5	0.10	0.23	0.10	.015	.006	.015	.002	8.0	1.25			79	4.71
e	11.7	8.7	2000	27.5*	5.0*	7.9	7.7	46	20	0.59	0.25	0.70	.025	.058	.085	.000	1.2	2.17	5.0	12.0		
120UP 1	123.3																					
p	250	5.0	2000	0.99	0.99	58.1	8.8	46.5	18.1	0.08	0.21	0.08	.011	.004	.015	.002	8.0	1.25			75	3.31
e	15.2	6.0	2000	32.0*	5.8*	6.8	5.7	47	18	0.69	0.32	0.70	.017	.036	.110	.000	1.2	1.50	9.9	23.7		
140UP 1	141.4																					
p	250	5.0	2000	0.99	0.99	58.1	9.3	46.5	18.6	0.08	0.20	0.08	.004	.001	.015	.002	8.0	1.25			81	1.17
e	20.0	2.0	2000	23.9*	4.3*	9.0	8.0	47	19	0.51	0.23	0.70	.017	.038	.145	.000	1.2	0.50	9.9	23.7		
30UP 2	31.6																					
p	50	0.9	4808	0.34	0.34	4.0	4.0	15.8	15.8	0.40	0.40	0.40	.015	.015	.015	.048	3.5	0.52			74	3.19
e	5.0	4.2	4808	11.0*	2.0*	2.3	12.7	16	16	0.69	0.12	0.70	.018	.099	.099	.000	1.2	2.50	4.0	9.6		
P44UP 2	44.7																					
p	55	1.2	4808	0.34	0.34	4.3	4.3	15.8	15.8	0.36	0.36	0.36	.015	.015	.015	.053	3.5	0.70			77	4.45
e	9.1	4.2	4808	9.9*	1.8*	2.5	14.0	16	16	0.63	0.11	0.70	.015	.081	.081	.000	1.2	2.50	4.0	9.6		
55UP 2	55.1																					
p	75	1.5	5198	0.34	0.34	5.9	4.3	15.8	13.4	0.27	0.31	0.27	.015	.013	.015	.036	3.5	0.95			77	6.55
e	10.1	3.8	5198	10.7*	1.9*	2.3	9.4	16	13	0.67	0.14	0.70	.017	.079	.079	.000	1.2	2.50	4.0	9.6		
100UP 2	98.6																					
p	208	2.0	5591	0.34	0.34	16.4	4.1	15.8	7.9	0.10	0.19	0.10	.015	.007	.015	.006	3.5	1.40			73	12.70
e	11.7	3.1	5591	10.9*	2.0*	2.3	3.2	16	8	0.69	0.25	0.70	.024	.066	.085	.000	1.2	2.18	5.0	12.0		
120UP 2	123.3																					
p	250	2.0	5591	0.34	0.34	19.8	4.9	15.8	7.9	0.08	0.16	0.08	.010	.005	.015	.004	3.5	1.40			74	8.87
e	15.2	2.1	5591	10.8*	2.0*	2.3	3.2	16	8	0.69	0.25	0.70	.018	.051	.110	.000	1.2	1.50	9.9	23.7		
140UP 2	141.4																					
p	250	2.0	5591	0.34	0.34	19.8	4.9	15.8	7.9	0.08	0.16	0.08	.003	.002	.015	.004	3.5	1.40			74	2.96
e	20.0	0.7	5591	10.8*	1.9*	2.3	3.2	16	8	0.68	0.25	0.70	.014	.039	.145	.000	1.2	0.50	9.9	23.7		

Appendix II: rf and IBS parameters

	Ep GeV	Np e11	f MHz	V MV	γ_t	sigz m	dp/p 10^{-4}	ν_z 10^{-3}	ϵ_{Nxy} μm	ϵ_z eV s	IBS long hr	IBS trans hr
30BL	50	3.00	197	0.6	23.5	0.200	6.056	2.69	2.50	0.020	1.02	2.49
140BL	250	3.00	197	3.8	23.5	0.200	6.039	3.31	2.50	0.101	11.60	5.36
30U1	50	0.18	493	1.8	23.5	0.080	6.527	7.25	0.70	0.009	2.24	1.33
140U1[a]	250	0.46	493	10.0	23.5	0.080	6.196	8.49	0.70	0.041	8.99	1.10
140U1[b]	250	0.46	493	5.0	23.5	0.080	4.381	6.00	0.70	0.029	3.32	0.81
30U2	50	0.14	1183	3.4	23.5	0.035	6.080	15.44	0.34	0.004	0.51	0.17
140U2[a]	250	0.19	1183	21.0	23.5	0.035	6.086	19.06	0.34	0.018	4.5	0.28
140U2[b]	250	0.19	1183	5.0	23.5	0.035	2.969	9.30	0.34	0.009	0.56	0.15

Note a) with very high rf volatage to minimize long emittance

Note b) with more moderate voltage